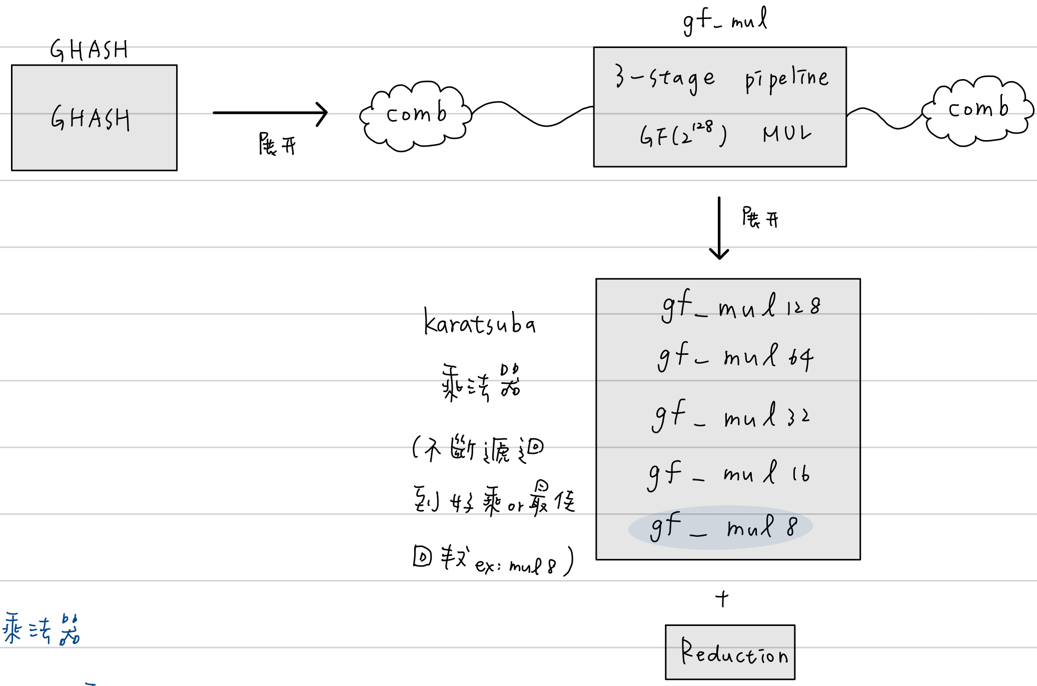
GHASH module



karatsuba

乘法器

(不斷遞迴

到好乘or最後

回數 ex: mul8)

乘法器

<一般> 看下一張

<二元有限域GF(2^8)><無modulo,最后会reduction>

$$\text{ex}: \{\overset{(a)}{57}\}\cdot\{\overset{(b)}{83}\} = \text{out}\ (\text{初始設 }00000000)$$

$$(01010111)\cdot(10000011)$$

$$\Rightarrow (x^6+x^4+x^2+x+1)\cdot(x^7+x+1)$$

$$x^6+x^4+\cancel{x^2}+\cancel{x}+1$$

$$= [(x^6+x^4+x^2+x+1)\cdot x] \overset{(\wedge)}{+}$$

b[0]=1, out = (a<<0) ^ out = 01010111

$$x^7+x^5+x^3+\cancel{x^2}+\cancel{x}$$

$$[(x^6+x^4+x^2+x+1)\cdot x^2] \overset{(\wedge)}{+}$$

b[1]=1, out = (a<<1) ^ (01010111) = 10101110 ^ 01010111 = 11111001

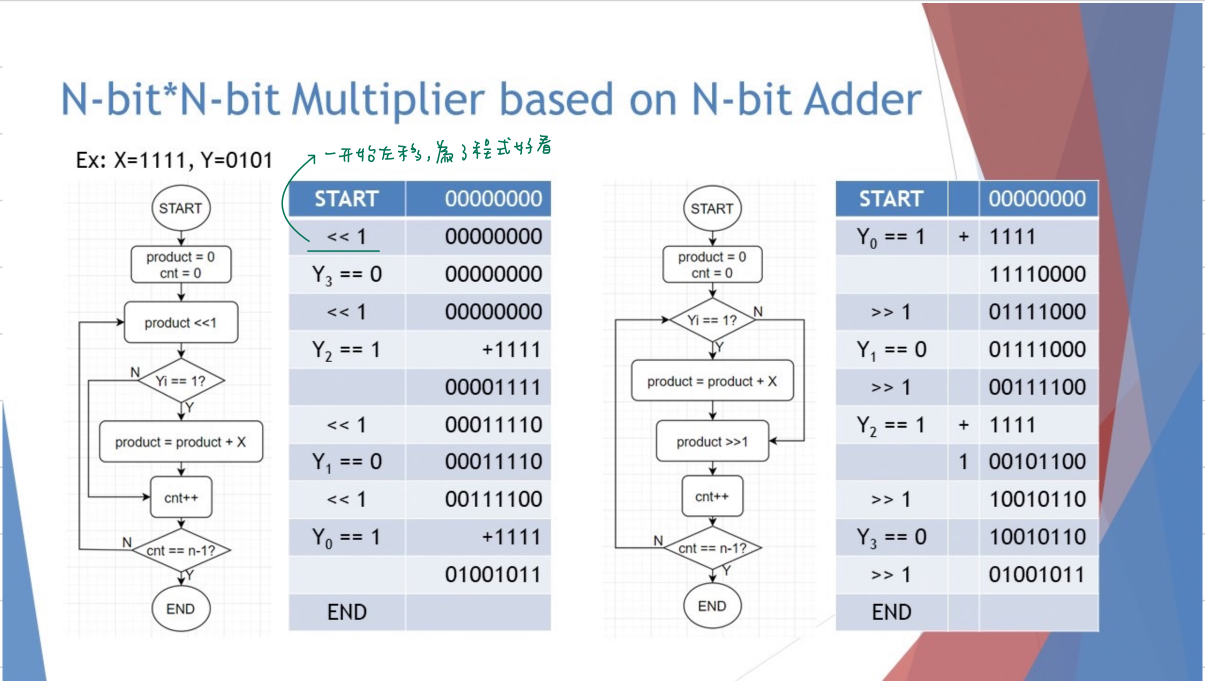
$$x^{13}+x^{11}+x^9+x^8+x^7$$

$$[(x^6+x^4+x^2+x+1)\cdot x^7]$$

b[7]=1, out = (a<<7) ^ (11111001) = 101011110000000 ^ 11111001 = 10101101111001

10101101111001

$$= x^{13}+x^{11}+x^9+x^8+x^6+x^5+x^4+x^3+1$$



N-bit*N-bit Multiplier based on N-bit Adder

Ex: X=1111, Y=0101

一开始左移，為了程式好看

START	00000000
<< 1	00000000
Y_3 == 0	00000000
<< 1	00000000
Y_2 == 1	+1111
	00001111
<< 1	00011110
Y_1 == 0	00011110
<< 1	00111100
Y_0 == 1	+1111
	01001011
END	

START		00000000
Y_0 == 1	+	1111
		11110000
>> 1		01111000
Y_1 == 0		01111000
>> 1		00111100
Y_2 == 1	+	1111
	1	00101100
>> 1		10010110
Y_3 == 0		10010110
>> 1		01001011
END		

＊只需看 y 是因為二進制（只有 1, 0），所以如果 yi=1 則加x並移位（乘1），yi=0 只需移位（乘0）

＊移位？

ex: 〈左移〉 <<1 跟平常運算相似

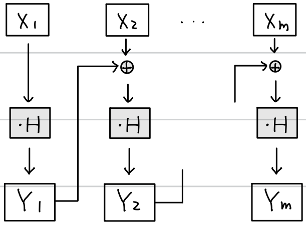
```
y3 start
y2                 1 2 5  (x)
y1               x 3 2 6  (y)
                   7 5 0
     <<1 <<1     2 5 0
<<1 <<1 <<1    3 7 5  ⟵
               4 0 7 5 0
```

```
                    000000
y3 start   <<1      000000
              +        375
y2         <<1      003750
              +        250
y3         <<1      040000
              +        750
                     40750 #
```

〈右移〉 >>1

```
          1 2 5  (x)
        x 3 2 6  (y)
          7 5 0
        2 5 0
      3 7 5
      4 0 7 5 0
```

```
y1 start     000000
         +   750
       >>1   075000
y2       +   250
       >>1   032500
         +   375
       >>1   040750 #
```



*每次的乘加運算都需要輸入上一次運算結果

AES 演算法

128 bits 組成一个狀態(state), state 為 AES 回合運算的基本單位。Key 長度不同, 分為 AES-128、AES-196、AES-256, 所需回合運算也不同

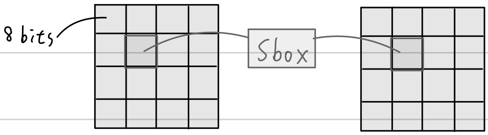
	128, 192, 256 密鑰長度(32 bits)	128 分組長度(32 bits)	10-14輪 加密輪數
AES-128	4	4	10
AES-192	6	4	12
AES-256	8	4	14

$a_0\ a_1\ a_2\ a_3\ \ a_4\ a_5\ a_6\ a_7\ \ a_8\ a_9\ \ a_{10}\ a_{11}\ \ a_{12}\ a_{13}\ a_{14}\ a_{15}$

a_0	a_4	a_8	a_{12}
a_1	a_5	a_9	a_{13}
a_2	a_6	a_{10}	a_{14}
a_3	a_7	a_{11}	a_{15}

127-120	95-88	63-56	31-24
119-112	87-80	55-48	23-16
111-104	79-72	47-40	15-8
103-96	71-64	39-32	7-0

* SubBytes 組合 Sbox 轉換



Sbox 單純轉換(一格)

SubBytes / InvSubBytes 是全部轉換, 呼叫 sbox

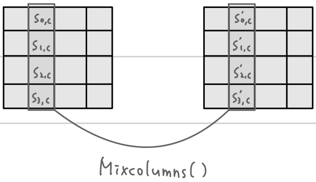
* shiftRows (列循環位移運算)

127-120	95-88	63-56	31-24	X
119-112	87-80	55-48	23-16	左 1
111-104	79-72	47-40	15-8	左 2
103-96	71-64	39-32	7-0	左 3

* InvShiftRows

127-120	95-88	63-56	31-24	X
119-112	87-80	55-48	23-16	右 1
111-104	79-72	47-40	15-8	右 2
103-96	71-64	39-32	7-0	右 3

* Mixcolumns (混行之轉換) & InvMixColumns (反轉換)



$S'(x) = a(x) \otimes S(x)$

$a(x) = \underset{0b}{\{03\}}x^3 + \underset{0d}{\{01\}}x^2 + \underset{09}{\{01\}}x + \underset{0e}{\{02\}}$

GF(2)

沒有⊕這位是因為只有八位！

* mul 1 (00000001) : 自己
* mul 2 (00000010) : 左移 << 1 , 若最高位 1 ⇒ overflow , modulo $\underline{8'h1b}$ (取餘數) ⊕ (二元域的 mod = ⊕) (00000001 → 00000010)
* mul 3 (00000011) : mul2 ⊕ 自己

$m(x) = \underline{x^8} + x^4 + x^3 + x + 1$

00011011

Mixcolumns & InvMixcolumns

$$\begin{bmatrix} S'_0 \\ S'_1 \\ S'_2 \\ S'_3 \end{bmatrix} = \begin{bmatrix} 02 & 03 & 01 & 01 \\ 01 & 02 & 03 & 01 \\ 01 & 01 & 02 & 03 \\ 03 & 01 & 01 & 02 \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}$$

$$\begin{bmatrix} 0e & 0b & 0d & 09 \\ 09 & 0e & 0b & 0d \\ 0d & 09 & 0e & 0b \\ 0b & 0d & 09 & 0e \end{bmatrix}$$

$S'_{0,c} = (\{02\} \cdot S_{0,c}) \oplus (\{03\} \cdot S_{1,c}) \oplus S_{2,c} \oplus S_{3,c}$

$S'_{1,c} = S_{0,c} \oplus (\{02\} \cdot S_{1,c}) \oplus (\{03\} \cdot S_{2,c}) \oplus S_{3,c}$

$S'_{2,c} = S_{0,c} \oplus S_{1,c} \oplus (\{02\} \cdot S_{2,c}) \oplus (\{03\} \cdot S_{3,c})$

$S'_{3,c} = (\{03\} \cdot S_{0,c}) \oplus S_{1,c} \oplus S_{2,c} \oplus (\{02\} \cdot S_{3,c})$

ex : $\{57\} \cdot \{83\} = \{c1\}$

mul2 的 7次 ⊕ mul2 的 1次 ⊕ 自己

$(x^6 + x^4 + x^2 + x + 1)(x^7 + x + 1)$

$(01010111)\underline{(10000011)}$

① $\Rightarrow (x^6 + x^4 + x^2 + x + 1) \cdot x = x^7 + x^5 + x^3 + x^2 + x$ (<< 1)

② $(x^7 + x^5 + x^3 + x^2 + x) \cdot x = \cancel{x^8} + x^6 + x^4 + x^3 + x^2 \bmod \cancel{x^8} + x^4 + x^3 + x + 1$

$= x^6 + x^2 + x + 1$ (<< 1)(再⊕1b)

③ $(x^6 + x^2 + x + 1) \cdot x = x^7 + x^3 + x^2 + x$

④ $(x^7 + x^3 + x^2 + x) \cdot x = \cancel{x^8} + x^4 + x^3 + x^2 \bmod \cancel{x^8} + x^4 + x^3 + x + 1$

$= x^2 + x + 1$ (<< 1)(再⊕1b)

⑤ $(x^2 + x + 1) \cdot x = x^3 + x^2 + x$ (<< 1)

⑥ $(x^3 + x^2 + x) \cdot x = x^4 + x^3 + x^2$ (<< 1)

⑦ $(x^4 + x^3 + x^2) \cdot x = x^5 + x^4 + x^3$ (<< 1)

① $(x^6 + x^4 + x^2 + x + 1) \cdot x = x^7 + x^5 + x^3 + x^2 + x$ (<< 1)

total (mul2 7次) ⊕ (mul2 1次) ⊕ 自己

$(x^5 + x^4 + x^3) \oplus (x^7 + x^5 + x^3 + x^2 + x) \oplus (x^6 + x^4 + x^2 + x + 1) = x^7 + x^6 + 1$ #

→ 3 个 function

這邊可寫在02,03 function裡)(09,0b,0d,0e 需重複呼叫才寫出 multiply function)

① ~~乘！的 function (multiply)~~

用來呼叫的 function { ② 02 ; ③ 03 }

(為了程式碼好看, so 多1个 01 function)

→ 5 个 functions

① 乘！的 function (multiply)

用來呼叫的 function {
② 09 (1001) ⇒ {02} 3次 ⊕ 自己
③ 0b (1011) ⇒ {02} 3次 ⊕ {02} ⊕ 自己
④ 0d (1101) ⇒ {02} 3次 ⊕ {02} 2次 ⊕ 自己
⑤ 0e (1110) ⇒ {02} 3次 ⊕ {02} 2次 ⊕ {02}

* AddRoundKey

in ⊕ key

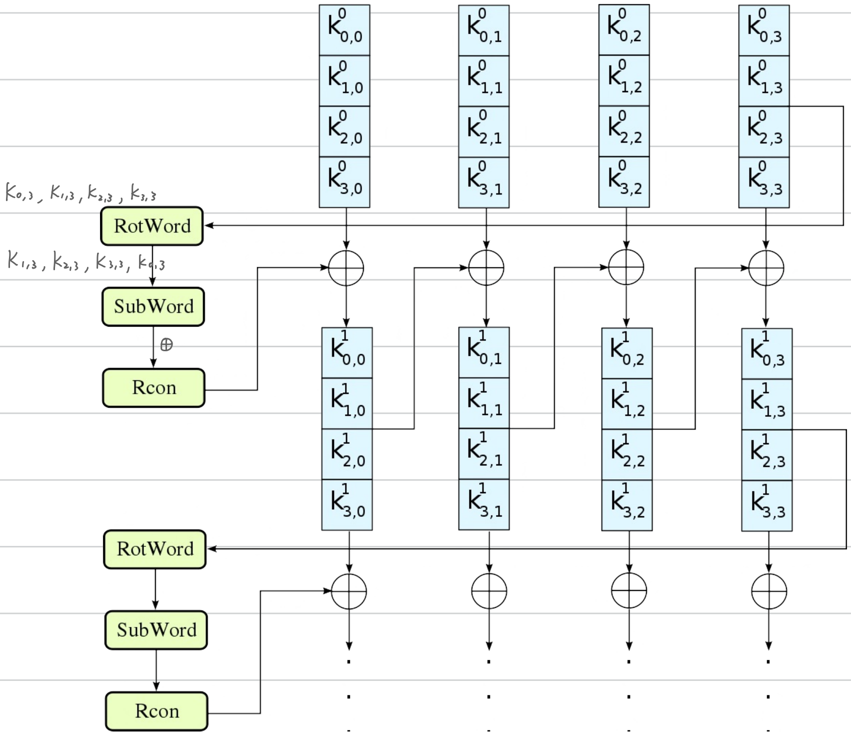
* Key Expansion

→ Rotword : $w[B_0, B_1, B_2, B_3]$ → Rotword → $w[B_1, B_2, B_3, B_0]$

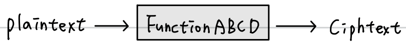
→ Subword : 用 Sbox 転換 (Sbox 一次 8 bits 転換 ⇒ 4次)

→ Rcon : 輸入回合數, 得該回合的回合常數 (对照表)

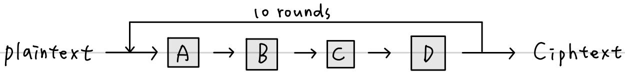
127-120	95-88	63-56	31-24
119-112	87-80	55-48	23-16
111-104	79-72	47-40	15-8
103-96	71-64	39-32	7-0


$K_{0,3}, K_{1,3}, K_{2,3}, K_{3,3}$
$K_{1,3}, K_{2,3}, K_{3,3}, K_{0,3}$
RotWord
SubWord
⊕
Rcon
$K^0_{0,0}$ $K^0_{1,0}$ $K^0_{2,0}$ $K^0_{3,0}$
$K^0_{0,1}$ $K^0_{1,1}$ $K^0_{2,1}$ $K^0_{3,1}$
$K^0_{0,2}$ $K^0_{1,2}$ $K^0_{2,2}$ $K^0_{3,2}$
$K^0_{0,3}$ $K^0_{1,3}$ $K^0_{2,3}$ $K^0_{3,3}$
$K^1_{0,0}$ $K^1_{1,0}$ $K^1_{2,0}$ $K^1_{3,0}$
$K^1_{0,1}$ $K^1_{1,1}$ $K^1_{2,1}$ $K^1_{3,1}$
$K^1_{0,2}$ $K^1_{1,2}$ $K^1_{2,2}$ $K^1_{3,2}$
$K^1_{0,3}$ $K^1_{1,3}$ $K^1_{2,3}$ $K^1_{3,3}$
RotWord
SubWord
Rcon

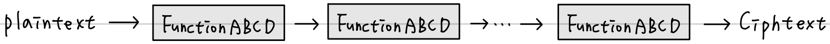
AES (top module)



*我的作法(area小)



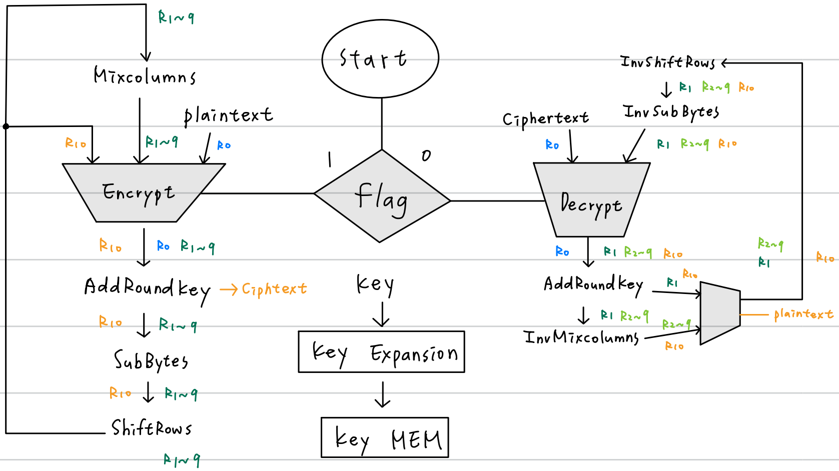
*任華的作法(throughput高)(area為我的10倍)

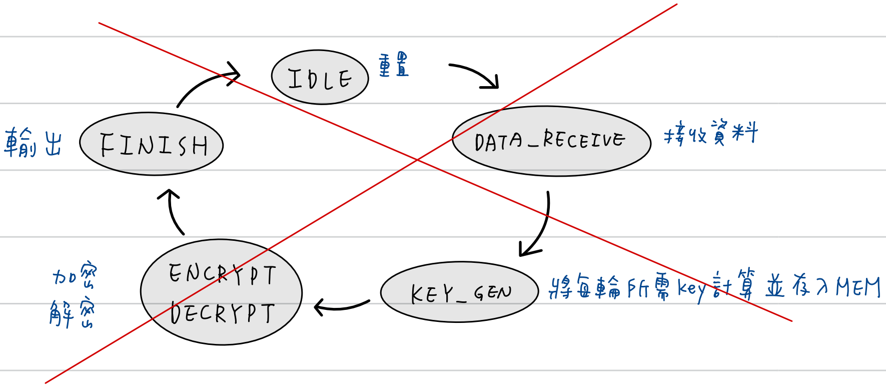


*兩个的 latency(延遲) same ⇒ 輸出第一筆 Ciphtext 時間 same

但任華的 throughput 高 ⇒ 假設第一筆輸出需 10 clk, 則 20 clk 時, 我的只有2个輸出, 任華有 11 个 (2倍)
(10倍)

*任華 aes 只有加密


Start
flag
1
0
Encrypt
Decrypt
Mixcolumns
R1~9
plaintext
R10
R1~9
R0
AddRoundkey
→Ciphtext
R10
R0 R1~9
R1~9
SubBytes
R10
R1~9
ShiftRows
R1~9
key
Key Expansion
key MEM
InvShiftRows
R1 R2~9 R10
InvSubBytes
Ciphertext
R0
R1 R2~9 R10
R0
R1 R2~9 R10
AddRoundkey
R1
R10
InvMixcolumns
R1 R2~9
R2~9
R10
R2~9
R1
R10
plaintext


IDLE
重置
DATA_RECEIVE
接收資料
KEY_GEN
將每輪所需key計算並存入MEM
ENCRYPT
DECRYPT
加密
解密
FINISH
輸出